Green hydrogen to reduce congestion: techno-economic analysis of a wind-powered electrolysis plant

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The Dutch Government is picking up the pace in the energy transition, of which the Climate Agreement is the embodiment. However, the increased installation of wind parks is facing challenges with grid congestion and curtailment. Onshore wind developers need to wait for the electricity infrastructure to be expanded. Therefore, hydrogen is an increasingly recurring topic of conversation in public discourse, since it is ideal for seasonal storage and large scale transport of energy. This research performs a techno-economic analysis of an electrolyser system next to a wind turbine, in order to relieve the strain on the electricity grid. The results of the simulations show that an electrolyser next to a wind turbine can be cost effective, but only if buyers are willing to pay a premium price for low carbon hydrogen.

***Index Terms*—Congestion, electrolyser, hydrogen, renewables, wind generation**

I. INTRODUCTION

Climate change is increasingly important in public discourse. In 2015, 197 countries signed the Paris Agreement, which states that these countries aim to hold the increase in global average temperature to well below 2 degrees Celsius compared to pre-industrial levels [21]. The Netherlands has been slow in reducing the emissions of greenhouse gasses. However, the national government aims to correct that situation with the climate agreement, which goal is to reduce greenhouse gas emissions by 49% in 2030 versus 1990 through a large-scale transformation of the built environment, mobility, industry, agriculture & land use and electricity sector [5].

Regarding electricity generation, the goal of the Dutch Government is to have 70% of the electricity from renewable sources by 2030 [5]. In 2019, the share of renewable electricity was 18% [2]. Since the Netherlands is relatively flat, the main options are wind and solar power. However, the electricity infrastructure is reaching it's capacity limits, since it was designed for central generation instead of decentralized generation [16]. As an example, figure 1 shows a map of the Northern Netherlands by the distribution grid manager Enexis, with the areas where no renewable connections are possible in red. Furthermore, as the share of renewable generation increases, the intermittency problem of renewables increase. This results in more curtailment, which has a negative effect on the return on investment of wind parks.

Several cases show how synergies between hydrogen and electricity networks can solve the problem of congestion in the power network and fast variation in the generation profile, without curtailment in the RES generation [1, 4, 18, 11]. On a transport system level, hydrogen is cheaper for the transport and storage of energy than electricity. The utilization of the natural gas grid for the transport of hydrogen can significantly reduce the investment in the expansion of the electricity grid. Furthermore, the storage of gas is favourable over storage of electricity in batteries over longer periods of time, while batteries are favourable for short term energy storage [15].

Alavi et al. [1], Farahani et al. [4] and Park Lee et al. [18] demonstrate an integrated approach to solve the mentioned issues with a synergy between electricity and hydrogen. However, the focus in these papers lies with the socio-technical analysis of the Car as Power Plant concept, not the techno-economic analysis of the production of hydrogen.

Jones and Powell [11] and Xydis and Mihet-Popa [25] investigate the integration of RES in an energy system including the storage of electricity and heat to solve the curtailment issues. Hydrogen is not considered in these studies. Khalid et al. [13] asses two hydrogen energy systems for a single house, with solar PV and wind power in combination with hydrogen storage, but these systems are only analysed from a technical point of view. Similarly, Waite and Modi [23] and Kavadias et al. [12] both analyse the implementation of electrolysis and hydrogen storage to prevent curtailment and grid congestion. However, these studies focus on the technical viability of these systems, the economic viability of the hydrogen production is not considered.

Concluding, the reviewed literature analyses the synergy between hydrogen and wind power to prevent congestion and curtailment, but merely from a technical point of view. Therefore, this paper presents a cost-benefit analysis of hydrogen production with electrolysis, to tackle grid congestion. First, wind turbines and an electrolyser are modelled according to their physical characteristics. Several electrolyser sizes are runned, in order to evaluate the effect on the key indexes to reflect the costs and benefits of the electrolyser system. The costs are the investment in the electrolyser system and bought electricity from the wind park, the benefits are the revenues from possibly selling the hydrogen, if the cost of production is lower than the market price of hydrogen.

II. CASE DESCRIPTION

The simulations are run for a place in the Northern Netherlands, called the Eemshaven, shown as a green dot in figure 1. This area hosts several wind turbines, and two extra parks are built, in order for the province of Groningen to fulfill their renewable generation targets. The new wind turbines are shown as red and blue dots in figure 2. However, as figure 1 points out, the expansion of wind generation in the area has reached its limits due to a lack of supporting infrastructure.

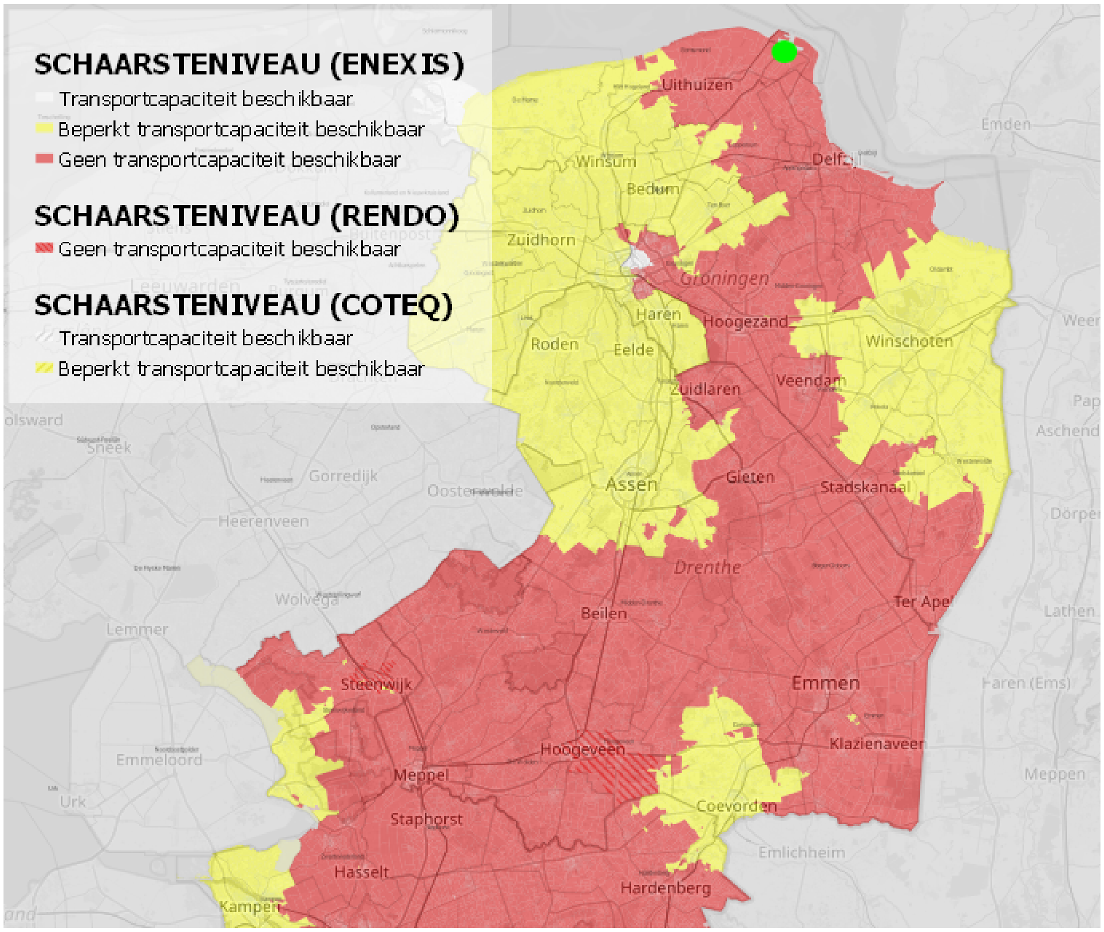

Figure 1. Scarcity of grid capacity at distribution grid manager Enexis in the Northern Netherlands [3]

If hydrogen needs to be transported for distances of less than about 1.500 km, transmission of hydrogen as a gas by pipeline is generally the cheapest option [10]. Besides that, many modern low-pressure gas distribution pipes are generally suitable to transport hydrogen with some minor upgrades. According to Kiwa Technology [14] the Dutch natural gas grid is capable of transporting 100% sustainable gasses, like hydrogen and bio-methane. Gasunie Transport Services (GTS), the gas transport company in the Netherlands, is developing a hydrogen backbone in the Netherlands, especially in the northern Netherlands. This infrastructure will have a capacity ranging from 10 to 15 GW which can be available from 2026 [7]. The backbone in Groningen starts in the Eemshaven, and consists of large scale storage in a salt cavern. Furthermore, Groningen Seaports, the port authority in the Eemshaven, announced that it will build a 4 km long hydrogen pipeline from Delfzijl to the Eemshaven [6].

III. RESEARCH APPROACH

This research is performed in an exploratory manner with a modelling approach. Simulations can provide insight into the possible operation of such a system, without real-life consequences, within an acceptable time frame [9]. A quantitative modelling approach is appropriate, since the quantitative analysis of the wind speed per hour over a year gives insight in the produced electricity and hydrogen per hour. The simulation model used in this research is called the PtX model. The simulations will run for several scenarios, in which the electrolyser size is altered. These scenarios are presented in section III-B. In order to get a realistic view of the wind generation, the wind speed data from the nearest weather station is used: KNMI Lauwersoog. Since the average wind speed per year differs from one to the other, the simulations are run for the wind speeds between 2015 and 2020.

A. *PtX model description*

The model used in this research is a deterministic model called the Power-to-X model (PtX), developed by Els van der Roest from the KWR Water Research Institute and used by van der Roest et al. [22]. This simulation model takes various economic and technical parameters as input, as well a the supply and demand patterns. Examples of these parameters are the price of electricity of hydrogen as well as the capacity of a wind turbine. With this information as input, together with a scheduling strategy, the PtX model creates an energy balance and delivers the associated system costs. A conceptual overview of the PtX simulation model is presented in figure 3.

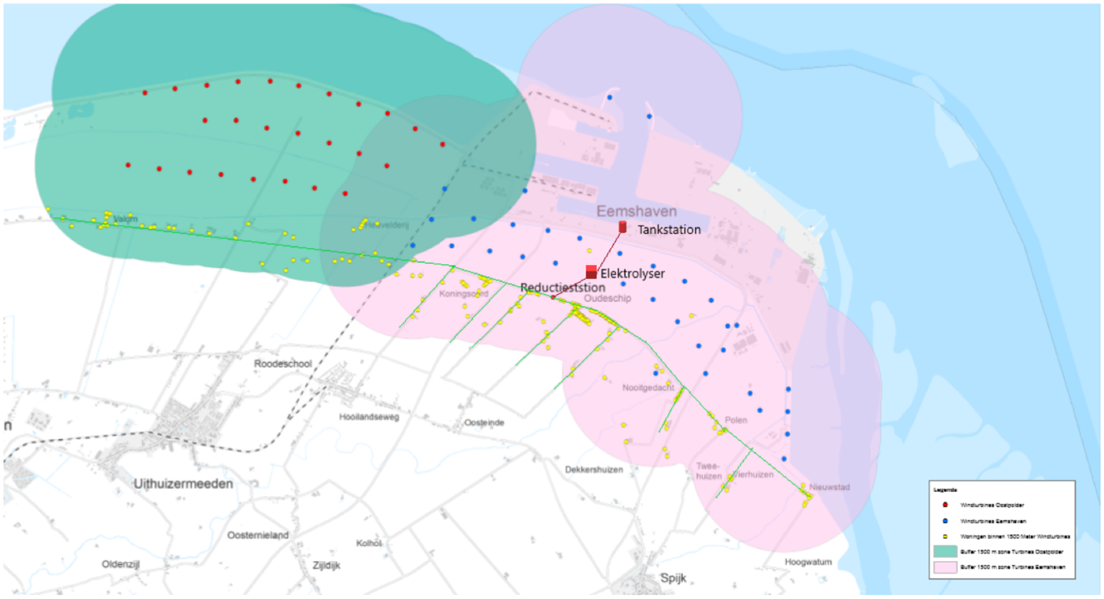

Figure 2. New turbines Eemshaven

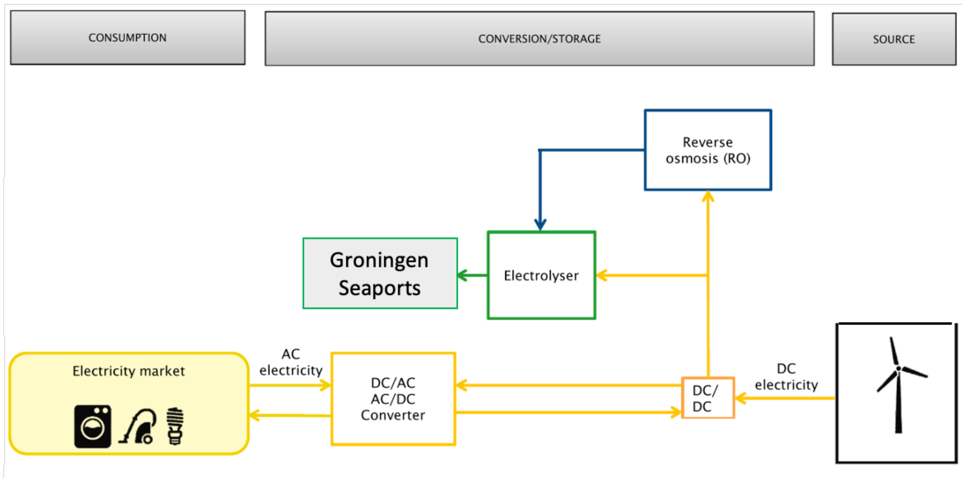

Figure 3. Flowchart PtX simulation model

B. *Design of Experiments*

A design of experiments is a systematic method to see the influence of process variables on the output of that process, as well as the relationship between those variables. As mentioned at the beginning of this paper, a design of experiments (DOE) is performed with altering values for the electrolyser capacity. The flows of the design of experiments is presented in figure 4. Since the electrolyser is coupled to a 4,5 MW wind turbine, and there is no use for the electrolyser to have a larger capacity than the turbine, the size of the electrolyser is varied to be 1 MW, 2 MW, 3 MW and 4 MW.

IV. MODELLING OF KEY ELEMENTS

This section starts with a short description of the proposed system design, and follows with a description of the main components in that design.

A. *Description electrolysis system*

An energy system with hydrogen as an energy carrier utilizes part of the electricity generated by the wind turbine to produce hydrogen. This hydrogen is transported through the existing gas infrastructure, owned and maintained by Enexis. An overview of this system is presented in figure 5.

It is assumed that the hydrogen produced by the electrolyser can be exported through this hydrogen infrastructure.

B. *Wind turbine*

Several of the wind turbines placed in the Eemshaven area are produced by a company called Lagerwey. The model of these wind turbines is the L136 with a maximum power output of 4.5 MW. This wind turbine is unique, since the power from the turbine can be either alternating current (AC) or direct current (DC) at 690 V, while standard turbines only have alternating current as output. That is helpful, since

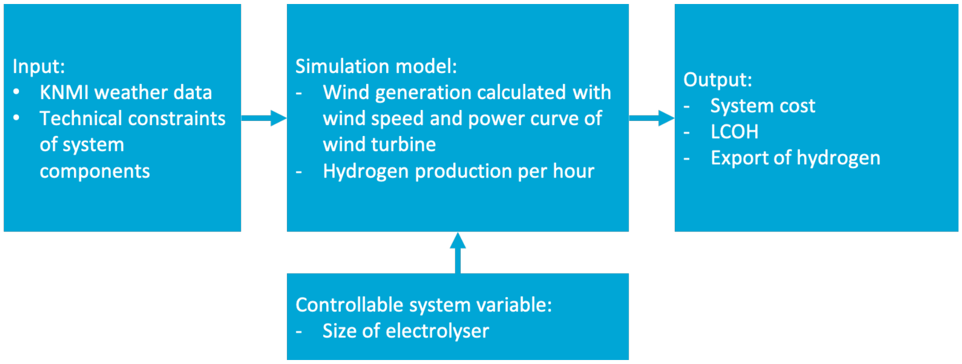

Figure 4. Flowchart of the DOE

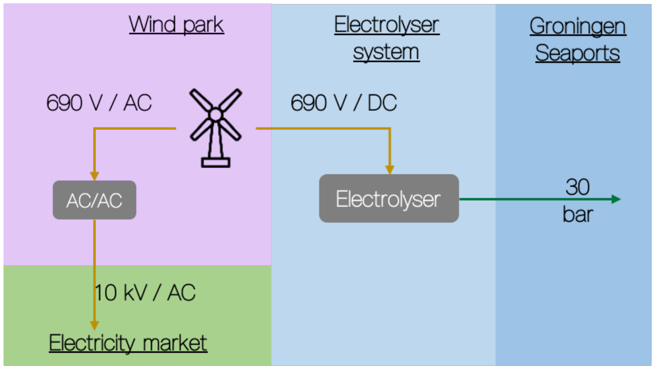

Figure 5. System design electrolysis

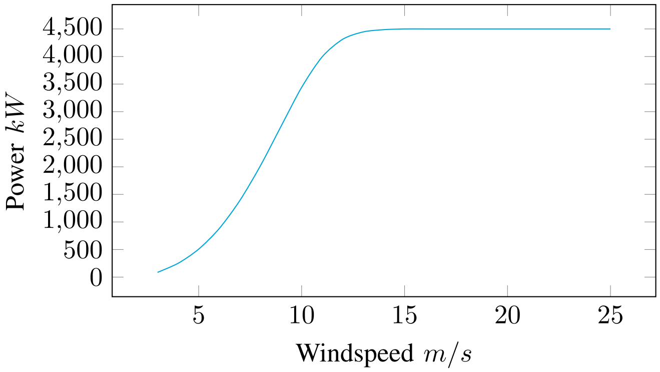

Figure 6. Power curve Lagerwey L136 wind turbine

electrolysers require direct current, while the standard on the electricity grid is alternating current, and the conversion from direct current to alternating current and vice versa includes losses. In order for the power to be fed in to the electricity grid, the power needs to be transformed from 690 V AC to 10 kV AC using a transformer.

The wind generation is calculated using the wind speeds measured at the nearest KNMI weather station at Lauwersoog. The power produced as a function of the wind speed at hub height is represented by a power curve. The power curve of the Lagerwey L136 turbine is shown in figure 6. When the wind speed is less than the cut-in wind speed, the turbine is not able to produce power. When the wind speed exceeds the cut-out speed, the wind turbine is stopped to prevent structural failures. In the case of the Lagerwey wind turbine, the cut-in speed is 2,5 m/s and the cut-out speed is 25 m/s.

One of the risks when investing in wind energy is the inconsistency of the wind resource compared to the forecast. To build a reliable business plan, investors analyse wind generation according to a so called P90 value. The P90 value is the level of annual generation that is predicted to be exceeded by 90% over a year. In this research, the wind generation of every hour is subtracted by 10% in order to get to this P90 value and safely predict the actual wind generation.

The wind speed meter of the KNMI weather station is placed at a height of 10 meters. However, the wind speed is higher at the hub height of the wind turbine. Therefore, the wind speed measurements need to be adjusted to hub height. A common mathematical model for accounting the variation of the horizontal wind speed with height is the log law, which can be used until the height of 60 meters. The log law is described by equation 1 where $u(h_2)$ is the wind-speed at height h_2, $u(h_1)$ is the wind-speed at height h_1, and z_0 is the surface roughness.

$$u(h_2) = u(h_1) * \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \tag{1}$$

The surface roughness, or roughness length, represents the roughness of the surrounding terrain. Typical surface roughness length values can be found in table I with corresponding descriptions of the terrain.

Since the area around the KNMI weather station is surrounded by a flat area, with only grass fields, a roughness length of 0,01 is used. At a certain height, the local effect of the earth surface roughness does not influence the boundary layer profile. This height is called the blending height. At this height, there is still an increase of wind speed with height, but the shape of that increase is no longer dependent on the Earth's surface. 60 meters is the blending height, at which the logarithmic lines converge. The wind speed at this height is called the meso wind speed. To calculate the wind speeds

Table I
TERRAIN ROUGHNESS CLASSIFICATION [24]

Class name	Roughness length z_0 (m)	Landscape description
Sea	0.0002	Open water, flat plain
Smooth	0.005	Obstacle-free land with negligible vegetation, marsh, ridge-free ice
Open	0.03	Flat open grass, tundra, airport runway, isolated obstacles
Roughly open	0.10	Low crops or plant cover, occasional obstacles
Rough	0.25	Crops of varying height, scattered obstacles with separation
Very rough	0.5	Intensively cultivated landscape with large farms, orchards, bushland; or low well-spaced buildings and no high trees
Skimming	1.0	Full similar-height obstacle cover with interspaces (mature forest, suburban town area)
Chaotic	≥ 2	Irregular distribution of very large elements: high-rise city centre, big irregular forest with large clearings

at heights above 100 meters, the power law of equation 2 is more appropriate. This equation also expresses the wind speed at the height h with the wind speeds at the reference height. The used reference height is the meso wind speed. Thus, the wind speed at meso height of 60 meters is calculated with the loglaw, after which this value is converted into the wind speed at hub height using the power law.

$$u(h_2) = u(h_1) * (\frac{h_2}{h_1})^{\alpha} \tag{2}$$

in which α is a constant value which differs for wind speeds over land and over sea. The constant used in this research is the standard value of α over land, which is $\alpha = 0,143$. With the roughness length value, equation 1 and equation 2, the hourly wind speed at hub height can be calculated. This is the wind speed at hub height for the location of the KNMI weather station. The required wind speeds are at the location of the Eemshaven, with a different roughness length, which influences the wind generation. However, since the landscape around the wind park at the Eemshaven is relatively similar, and the hub height is above the blending height, the wind speeds at hub height at the weather station and at the Eemshaven are assumed to be the same.

The wind speed that is acquired through the calculations presented above are combined with the power curve presented in figure 6 in order to calculate the generated wind power.

C. Electrolyser

Electrolysers use electricity and water to produce hydrogen and oxygen. There are currently three main electrolyser technologies: alkaline electrolysis, Polymer Electrolyte Membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOECs). *Alkaline electrolysis* is a mature technology and commercially available. Dynamic operation is limited which makes it unfavourable in combination with solar PV. However, since wind generation is not as dynamic, an Alkaline electrolyser is a possibility [20]. This type of electrolysis has relatively low capital costs due to the avoidance of precious materials. Since *PEM electrolysers* need electrode catalysts like platinum and iridium, and membrane materials, they are relatively expensive. Furthermore, their lifetime is shorter than alkaline electrolysers and they are less widely deployed. *SOECs* are less developed and not yet commercialised. Therefore, this type of electrolysis is not considered in this study. The technical and economic properties of an Alkaline and PEM electrolyser are presented in table II. Due to the higher investment cost and lower efficiency, it is clear that an Alkaline electrolyser suits the purpose of electrolysis with wind power.

The electrolyser uses electricity and water to produce hydrogen and oxygen. To ensure a long lifetime of an electrolyser, the feed-in water should be of a pure quality. Therefore, reversed osmosis for the water purification is necessary. The energy required for the purification of the water is taken into account, which is 1.3 kWh/kg H_2 [17]. The supply of water can be rain water, surface water or tap water. Typical electrolysers require DC power at a voltage which differs per producer and requirements by the customer. The electricity from these specific turbines is at 690 V. It is assumed that the electrolyser has an internal DC/DC converter to get from 690 V to the required lower voltage. The efficiency of a DC/DC transformer is assumed to be 95% [22].

V. ECONOMICS OF THE SYSTEM

A. Electricity tariff

The subsidy Stimulering Duurzame Energieproductie (SDE+) is an exploitation subsidy to subsidize renewable generation. In order to calculate the subsidy, it makes use of a base amount, and a base energy price. The base amount is the cost of production per kWh, including a profit margin. The subsidy covers the difference between the base amount and the market price for electricity. The base energy price is the minimum market price up to which the subsidy will rise. The Eemshaven is in the municipality Het Hogeland, which has an average wind speed of more than 8 m/s [19]. For this average wind speed, the base amount is 0,042 €/kWh, and the base energy price is 0,029 €/kWh. Therefore, if the market price is higher than 0,029 €/kWh, the subsidy will cover the difference between that market price and the base amount of 0,042 €/kWh, until the market price is higher than the base amount. When the market price for electricity dives below 0,029 €/kWh, the subsidy has reached its maximum.

For this research, it is assumed that the electricity from the wind turbines is bought by the operator of the electrolyser system for 0,029 €/kWh. Next to the electricity supply to the electrolyser, the remainder of the electricity is sold on the electricity market for market price, which is not taken into account in this research.

B. Economic calculations

1) Total cost of electrolysis system

The Total Cost TC of the electrolysis system are calculated with the annual capital cost CC (€/year), operational and

Table II
TECHNO-ECONOMIC CHARACTERISTICS OF DIFFERENT ELECTROLYSER TECHNOLOGIES [10]

	Alkaline electrolyser	**PEM electrolyser**
Electrical efficiency (%, HHV)	83	71
Energy per kg (kWh/kg H_2)	47.5	55.5
Operating pressure (bar)	1 - 30	30 - 80
Stack lifetime (years)	20	20
Cold-start time (min.)	60	20
Gas purity (%)	99.5	99.99
CAPEX (€/kW)	500	1100
OPEX (%/year) [a]	2.7	2.7

[a] [17]

maintenance cost OMC (€/year) and annual cost of electricity EC (€/year):

$$TC(€/year) = CC + OMC + EC \tag{3}$$

The CC (€/year) of the electrolyser is calculated with the annuity factor AF (%), installed component capacity Q (component specific capacity) and investment cost IC (€/component specific capacity):

$$CC(€/year) = AF * Q * IC \tag{4}$$

The annuity factor AF is based on the weighted average cost of capital WACC (%) and the economic lifetime of the component LT (years):

$$AF = \frac{1-(1+WACC)^{-LT}}{WACC} \tag{5}$$

The annual operations and maintenance costs OMC (€/year) are expressed as an annual percentage OM (%) of the Q and IC:

$$OMC(€/year) = OM * Q * IC \tag{6}$$

A WACC of 3% is used.

2) Levelized cost of hydrogen

The Levelized Cost of Hydrogen, $LCOH$ (€/kg H_2), is calculated by dividing the total cost TC by the annual hydrogen production HP (kg H_2/year):

$$LCOH(€/kgH_2) = \frac{TC}{HP} \tag{7}$$

VI. ASSUMPTIONS

For clarity, the assumptions made for the simulations are listed below:

- An unlimited amount of hydrogen can be sold through the hydrogen network of Groningen Seaports
- The electrolyser has an internal DC/DC converter
- The wind speed at hub height in the Eemshaven is the same as the wind speed at hub height at Lauwersoog
- The electricity from the wind turbine is bought for 0,029 €/kWh

VII. SIMULATION RESULTS

The simulations of the proposed electrolysis system show that the wind turbines have an average load factor of 42%. Figure 7 and figure 8 show the distribution of the wind power with a 1 MW and 3 MW electrolyser, respectively. While the 1 MW electrolyser receives a relatively stable supply of electricity, the 3 MW electrolyser is more susceptible to the fluctuations in generation. Since the wind turbine has a capacity of 4,5 MW, it is more likely to produce a minimum of 1 MW than 3 MW during the year.

As shown in figure 9, which shows the average hydrogen production per month over the 5 simulated years. The 1 MW electrolyser produces a steady supply of hydrogen. However, the bigger the capacity of the electrolyser, the closer it comes to the capacity of the wind turbine. Therefore, a larger electrolyser will receive a relatively lower volume of electricity per MW of electrolyser capacity. As can be deducted from figure 9, the larger the electrolyser gets, the more it becomes susceptible to the fluctuations in generation. This effect is also apparent from the development of the LCOH.

Figure 10 shows the Levelized Cost of Hydrogen per electrolyser size. Clearly, the smaller the size of the electrolyser in comparison to the size of the wind turbine, the lower the LCOH. This is expected, since the load factor of the electrolyser will be large for most of the time if a relatively large wind turbine is generating at a low percentage of its capacity. It should be noted that the shown LCOH is excluding taxes and transport costs.

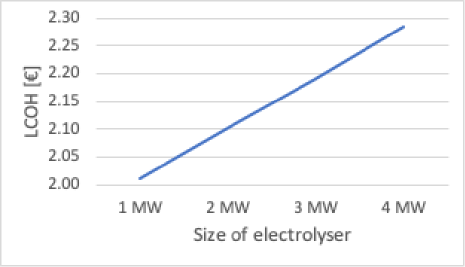

Figure 10. Levelized Cost of Hydrogen

To analyse the viability of the business case of a wind powered electrolysis system, the market price of hydrogen is important. There are currently three main categories of hydrogen: grey hydrogen with steam methane forming from natural gas, blue hydrogen through steam methane forming from natural gas with carbon capture and storage, and green

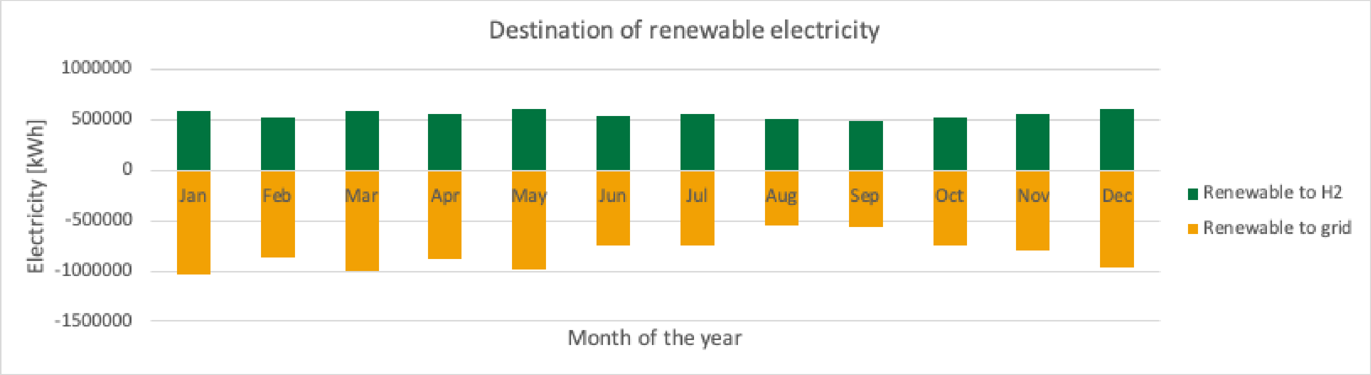

Figure 7. Distribution of wind power with a 1 MW electrolyser

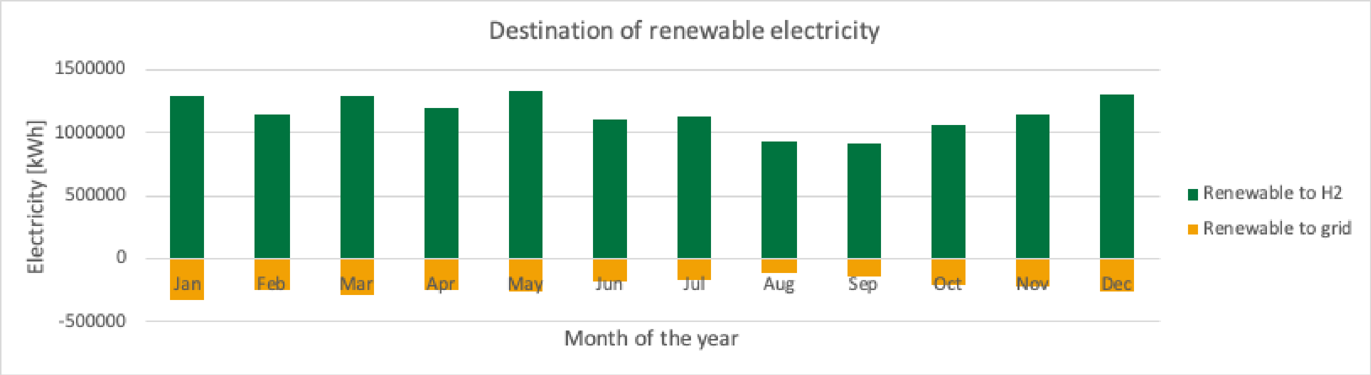

Figure 8. Distribution of wind power with a 3 MW electrolyser

Table III
SIMULATION RESULTS

	1 MW	**2 MW**	**3 MW**	**4 MW**
LCOH	2.01	2.10	2.19	2.29
Elec cost	194408	316409	403944	463384
IC	500000	1000000	1500000	2000000
OM	13500	27000	40500	54000
Total cost/y	260589	448766	602456	727981

hydrogen from electrolysis. Grey hydrogen is estimated to cost between 1,50 and 2,50 €/kg, blue hydrogen between 2,25 - 3,25 €/kg and green hydrogen between 3 and 6 €/kg [8]. All of these prices exclude taxes and transport costs. The LCOH calculated in this research points out that green hydrogen can be produced for a lower price if the electrolyser is placed at the location of electricity production. As most of the hydrogen sold in the Netherlands is grey hydrogen, the current market price is lower than the LCOH found in this research. Therefore, the business case is only profitable if a buyer of hydrogen is willing to pay a premium price for low carbon hydrogen.

As wind parks can not be built or have to remain smaller than planned due to infrastructure limitations, hydrogen can start to play a role. For instance, it is assumed that the Eemshaven wind park is planned to expand with 9 extra turbines of 4,5 MW. If the distribution grid operator only allows for a 22,5 MW connection, a 18 MW electrolyser could be installed. This electrolyser can potentially produce green hydrogen for 2,10 €/kg.

VIII. DISCUSSION

Purely from a cost perspective, grey hydrogen is less expensive than the hydrogen produced in the proposed design. However, this hydrogen was produced with a fixed electricity tariff of 0,029 €/kWh, which is higher than the average electricity market price. If the electricity market price is used, the LCOH would be lower. Furthermore, the capital loss of curtailment was not taken into account in this example, which might push the LCOH down. Next to that, the carbon reduction targets are high, and the carbon price is rising. As the carbon price rises, so does the price of grey hydrogen. Therefore, the business case of green hydrogen might become more profitable within a few years.

IX. CONCLUSION

This research looks into the synergy between wind power and hydrogen in order to avoid congestion on the electricity grid. The simulations show that the green hydrogen can be produced for prices between 2,00 and 2,29 €/kg, which is slightly higher than the average price for grey hydrogen. Since grey hydrogen dominates the hydrogen market, the business

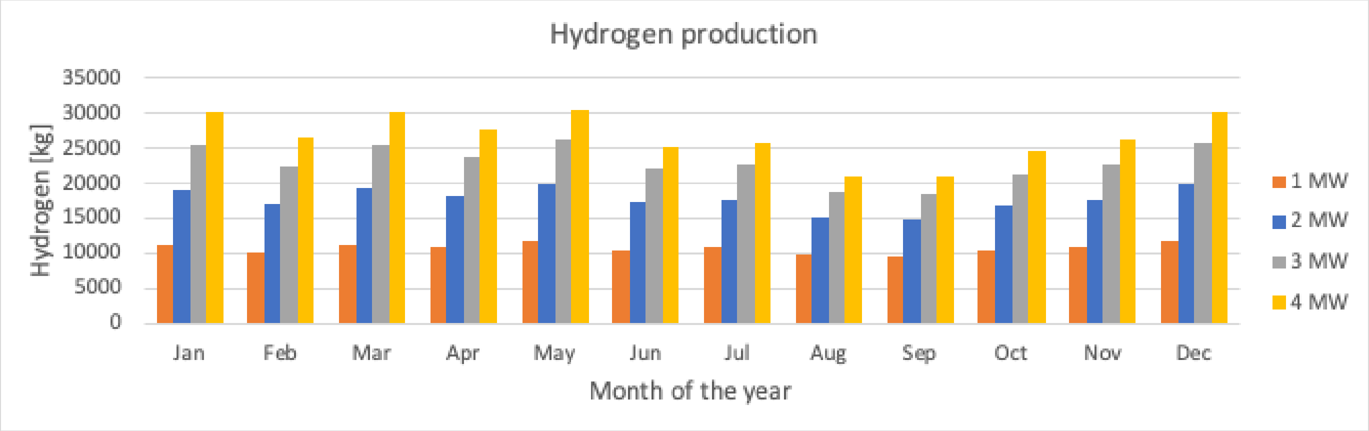

Figure 9. Average hydrogen production per month

case is only positive if a buyer of hydrogen is willing to pay a premium price for low carbon hydrogen, or if a local buyer is found, which saves on hydrogen transport compared to a grey alternative. Future research should look into the addition of capital loss due to curtailment in the formation of the LCOH. Moreover, a prediction of the carbon price would give insight into the future of the business case of green hydrogen. Lastly, the business case is formed by having the wind park developer and electrolyser operator to agree on a fixed electricity price of 0,029 €/kWh, which will be different if the electricity market price is used.

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